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A survey of dynamic equivalent modeling for wind farm

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ABSTRACT

With the increasing of grid connected wind power capacity, dynamic equivalent modeling for large wind farm have become more and more important as the tool to analyze the influence of power system stability with large-scale grid-connected wind farms. Recently doubly-fed induction wind generator (DFIG) has become the mainstream wind turbine used in wind farm for its virtue in wind power conversion efficiency and active power regulation activity. Thus, DFIG based wind farm has attracted more and more attention. This paper provided an overview of dynamic equivalent modeling for wind farm. At first, the structure of DFIG dynamic model, the principle and characteristic of each part are introduced. Secondly, various dynamic equivalent modeling methods for wind farm, including single-machine representation method and multi-machine representation method, are discussed in details. Meanwhile, the calculation methods for equivalent unit parameters for multi-machine representation based modeling are discussed. Finally the current researches and existing problems of the dynamic equivalent modeling for wind farm are summarized.

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Contents

1. Introduction

As the main form in the wind energy utilization, wind power is one of the power generations with the mature development, cheaper cost and larger scale exploitation in all kinds of new energy technology at present. More and more countries pay increasingly

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Nomenclature

V	wind speed (m/s)
ρ	air density (kg/m^3)
A_r	area of wind turbine blades (m^2)
T_m	mechanical torque of generator rotor (N⁎m)
T_M	mechanical torque of wind turbine terminal shaft (N⁎m)
u_{ds}, u_{qs}	d/q axis voltage of stator (V)
u_{dr}, u_{qr}	d/q axis voltage of rotor (V)
i_{ds}, i_{qs}	d/q axis electrical current of stator (kA)
i_{dr}, i_{qr}	d/q axis electrical current of rotor (kA)
ψ_{ds}, ψ_{qs}	d/q axis magnetic flux of stator (Wb)
ψ_{dr}, ψ_{qr}	d/q axis magnetic flux of rotor (Wb)
R_s, R_r	wire-wound resistors of stator and rotor (Ω)
ω_e	rotational angular velocity of generator (rad/s)
L_s, L_r	self induction of stator and rotor (mH)
β	pitch angle (deg)
P	active power (k_W)
S	capacity of wind generator (k_W)
C	wind generator compensation capacitor (uF)
Z_G, Z_T	wind generator impedance and terminal impedance of transformer (Ω)

attention to wind power. Meanwhile, it has been exploited and utilized widely [1,2].

With the rapid development of wind power industry, the number of large-scale wind farm with 100 MW and above increases quickly all over the world. Meanwhile, the capacity of wind power integrating into power grid is growing, its influences to power grid becomes more and more significant [3,4]. The operation dynamic characteristic of wind farm decides its influence degree to power system. Thus, a lumped model which can be able to reflect operation dynamic characteristic of whole wind farm accurately is the foundation to carry out the further analysis and research for the grid connected wind farm.

In general, a large-scale wind farm is constituted with hundreds or thousands of wind turbines. If modeling each wind turbine in sequence to calculate the dynamic operation characteristic of wind farm, the data preparation and model calculation earns a significant amount. This direct wind farm modeling undoubtedly enlarge the complexity of its simulation model, and has shortcomings such as long simulation time and low efficiency, which limits its practical engineering application. On the other side, the analysis and research of grid-connected wind farm mainly focus on the dynamic characteristic of power output of whole wind farm, neither the particular feature of each wind turbine.

Therefore, in order to achieve the demand of the dynamic characteristic analysis for the wind farm integrating in power grid, the study of dynamic equivalent model for the large-scale wind farm has attracted more and more attention. Now, there are many methods to build the dynamic equivalent model for the large-scale wind farm. However, these methods have each characteristics and different background and condition. Meanwhile, recently, doubly-fed induction generator (DFIG) has been used as mainstream wind turbine in wind farm for its merits in efficiency and electrical performance. Thus, this paper summarizes and classifies the current methods on dynamic equivalent modeling of doubly-fed-based wind farm.

This paper which reviews the dynamic equivalent modeling method of doubly-fed-based wind farm, is organized as follows. In Section 2, the dynamic model of DFIG is introduced. This follow by the dynamic equivalent modeling methods of doubly-fed wind farm, including single-machine representation and multi-machine representation method are reviewed in Section 3. The single-machine representation based modeling method is classified into "1+1" and "1+n" model modeling, which are discussed in Section 3.1 in detail. The Multi-machine representation methods for the regular and irregular wind farm are discussed in Section 3.2. In Section 4, the paper summarizes the research profile and the challenge of the dynamic equivalent modeling for the wind farm.

2. Dynamic model of wind turbine

The wind turbine used in wind farm can be approximately divided into fixed speed wind turbine (FSWT), direct-driven permanent magnet synchronous generators (PMSG) and doubly fed induction generator (DFIG) [5]. Among them, DFIG has become the current mainstream wind turbine due to its advantage of wide range of timing, high wind energy utilization effectiveness, small capacity in excitation converter and the flexible regulation in active and reactive power [6]. Therefore, establishment of the accurate dynamic model to reflect the output characteristic of DFIG is the foundation to conduct the dynamic equivalent modeling of DFIG-based wind power farm and to perform the subsequent research for the analysis of dynamic characteristic with the wind power integration.

The dynamic model of DFIG is mainly comprised with five sub-models, including wind speed model, wind turbine model, transmission mechanism model, generator model and control system model, as shown in Fig. 1.

2.1. Wind speed model

Wind energy is the motive power of wind turbine with the characteristic of randomness and intermittence. The variation of wind speed can affect the dynamic characteristic of wind turbine in a direct way. So the combined speed model is often adopted in the related research with four components, including basic wind V_b, gust wind V_g, gradient wind V_r and random wind V_n, to simulate the variation of the wind speed [7].

(1) Basic wind

$$V_b = A\Gamma\left(1+\frac{1}{K}\right) \tag{1}$$

where A, K are scale parameter and shape parameter of Weibull Distribution; Γ is gamma function.

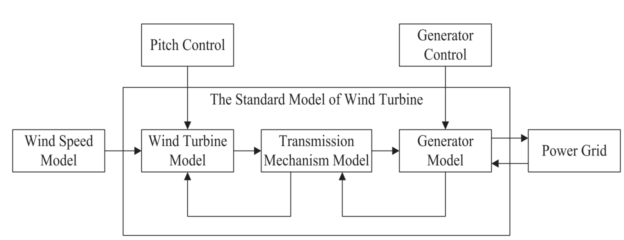

Fig. 1. The dynamic model of DFIG.

(2) Gust wind

$$V_g = \begin{cases} 0 & t < T_{gc} \\ \frac{1}{2} V_{g\_max}\left[1 - \cos\left(\frac{2\pi}{T_{gs}} t - \frac{T_{gc}}{T_{gs}}\right)\right] & T_{gc} \le t < T_{gc} + T_{gs} \\ 0 & t \ge T_{gc} + T_{gs} \end{cases} \quad (2)$$

T_{gc}, T_{gs}, V_{g_max} are start time, period and maximum value of gust wind, respectively.

(3) Gradient wind

$$V_r = \begin{cases} 0 & 0 < t < T_{rs} \\ V_{r\_max}\left[1 - \frac{t}{T_{rt}(T_{rs} - T_{rt})}\right] & T_{rs} \le t < T_{rt} \\ V_{r\_max} & T_{rt} \le t < T_{rt} + T_{rc} \\ 0 & t \ge T_{rt} + T_{rc} \end{cases} \quad (3)$$

where
T_{rs}, T_{rt}, T_{rc}, V_{r_max} are start time, terminal time, retention time and maximum value of gradient wind, respectively.

(4) Random wind

$$V_n = 2 \sum_{i=1}^{N} \sqrt{S_V(\omega_i)\Delta\omega}\ \cos(\omega_i + \varphi_i) \quad (4)$$

where

$$\omega_i = \left(i - \frac{1}{2}\right)\Delta\omega$$

$$S_V(\omega_i) = \frac{2K_N F^2 |\omega_i|}{\pi^2 \left[1 + \left(\frac{F\omega_i}{\mu\pi}\right)^2\right]^{4/3}} \quad (5)$$

φ_i are random variables distributed uniformly between 0 and 2π; K_N is the coefficient of surface roughness; F is the range of disturbance; μ is average wind speed of relative height; N is the number of sampling points; ω_i is the frequency of each frequency band.

The above four component constitutes the wind speed of wind turbine.

$$V = V_b + V_g + V_r + V_n \quad (6)$$

The combined wind speed model is usually used in the power system analysis software PSCAD/EMTDC [8], but it is found that the wind speed model cannot simulate the variation of wind speed comprehensively and accurately.

Therefore, another combined wind speed model is proposed in [9,10]. The model is combined with average components and turbulent components. The average components are assumed to remain constant in a short time, turbulent components are used to reflect the variation of the wind speed. In [11], based on the research of statistical characteristic for the wind power, a wind speed model with the autoregressive moving average method (ARMA) to reflect the characteristic of power density is further proposed. Besides, a wind speed model for the wind speed disturbance suggested in [12], which considers the wake effect between the units; this model can capture the fluctuation of output power accurately.

2.2. Wind turbine and transmission mechanism model

Wind turbine is used for converting wind energy to mechanical energy. Based on the principle of aerodynamics, the output of mechanical power for the wind turbine can be stated as follows [13]:

$$P_M = (1/2)\rho A_r V^3 C_p(\lambda, \theta) \quad (7)$$

where $C_p(\lambda, \theta)$ is the power coefficient with a set of nonlinear curve and the theoretical maximum is 0.593.

Due to the action of transmission between wind turbines and generators, some time delay exists. The first order inertial elements model is commonly used to simulate the transmission device [14]

$$\frac{dT_m}{dt} = \frac{1}{T_d}(T_M - T_m) \quad (8)$$

where T_d is the inertia time constant of the mechanical transmission mechanism.

2.3. Generator model

Generally, DFIG adopts the winding asynchronous generator and obtains its dynamical model under the dq coordinate system. The corresponding basic voltage equation and flux linkage equation is given as follows as in [15–17].

(1) Voltage equation

$$\begin{aligned} u_{ds} &= R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \psi_{qs}\omega_e \\ u_{qs} &= R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \psi_{ds}\omega_e \\ u_{dr} &= R_r i_{dr} + \frac{d\psi_{dr}}{dt} - \psi_{qr}\omega_s \\ u_{qr} &= R_r i_{qr} + \frac{d\psi_{qr}}{dt} + \psi_{dr}\omega_s \end{aligned} \quad (9)$$

where ω_s is slip angular velocity relative to the rotor.

(2) Flux linkage equation

$$\begin{aligned} \psi_{ds} &= L_s i_{ds} + L_m i_{dr} \\ \psi_{qs} &= L_s i_{qs} + L_m i_{qr} \\ \psi_{dr} &= L_r i_{dr} + L_m i_{ds} \\ \psi_{qr} &= L_r i_{qr} + L_m i_{qs} \end{aligned} \quad (10)$$

where L_m is mutual induction of stator and rotor.

The above dynamic model of DFIG contains the influence of flux increment for stators and rotors to the dynamic characteristic of generator. But the complexity of the model limits the feasible application in actual simulation. Therefore, another DFIG dynamic model with lower order by neglecting the flux transient process of stators is proposed in [18,19]. The simulation result shows the simplified model can preferably represent the dynamic characteristic of doubly-fed generator and can effectively apply to the analysis of dynamic issues for the wind farm.

2.4. Control system model

Control system of DFIG mainly consists of grid-side converter control, rotor-side converter control, pitch control and speed control [20,21].

(1) Vector control of grid-side converter

Grid-side converter adopts the stator voltage oriented vector control method for maintaining the dc-bus voltage stability. In the d–q synchronous rotating reference coordinate, the voltage equation of grid-side converter can be stated as follows:

$$\begin{aligned} u_d &= -R_g i_{gd} - L_g \frac{di_{gd}}{dt} + \omega_s L_g i_{gq} + u_{gd} \\ u_q &= -R_g i_{gq} - L_g \frac{di_{gq}}{dt} - \omega_s L_g i_{gd} + u_{gq} \end{aligned} \quad (11)$$

where u_d, u_q are grid voltages for the d and q axial respectively; $u_{gd}, u_{gq}, i_{gd}, i_{gq}$ are voltages and electric currents of grid-side converter for the d and q axial respectively.

According to the equations above, the control block diagram is shown in Fig. 2. It adopts PI controller. i_{gd} controls the dc-bus voltage, i_{gq} controls the reactive power exchange between rotor and grid.

(2) Vector control of rotor-side converter

Rotor-side converter adopts the flux oriented vector control method to finish the dynamic decoupling control of stator terminal output active power and reactive power of doubly-fed generator. In the d–q synchronous rotating reference coordinate, the voltage equation of rotor-side converter can be stated as follows:

$$u'_d = R_r i_{rd} + \sigma L_r \frac{di_{rd}}{dt} - (\omega_s - \omega_e)\sigma L_r i_{rq}$$
$$u'_q = R_r i_{rq} + \sigma L_r \frac{di_{rq}}{dt} + (\omega_s - \omega_e)\left(\frac{L_m}{L_s}\psi_s + \sigma L_r i_{rd}\right)$$
$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \tag{12}$$

where u'_d,u'_q are rotor voltages for the d and q axial respectively; i_{rd},i_{rq} are electric currents of rotor-side converter for the d and q axial respectively.

According to the equations above, the control block diagram is shown in Fig. 3. It also adopts PI controller. i_{rq} controls the active power and i_{rd} controls the reactive power.

(3) Pitch control

Pitch control indicates the wind turbine blade can adjust the magnitude of pitch on the basis of wind dynamic characteristic to control the output power of DIFG and to limit the mechanical power of wind turbine under high wind speed. The dynamic mathematical model of pitch control can be stated as first order differential equation

$$\frac{d\beta}{dt} = \frac{1}{\tau}(\beta_{ref} - \beta) \tag{13}$$

where β_{ref} is the reference command of pitch angle; τ is time constant of controller.

Suppose that $\beta_{ref} = f(C_p, \lambda)$, where C_p is the power coefficient and λ is blade top speed ratio. The control block diagram is shown in Fig. 4.

(4) Speed control

Speed control indicates DFIG can adjust the speed of wind turbine to control output power. It is realized by adjusting electromagnetic torque T_e. The equation of T_e can be stated as follows:

$$T_e = |\overline{u}_s| i_{qs}$$
$$i_{qs} = \frac{L_m}{L_m + L_s} i_{qr} \tag{14}$$

where $\dot{u}_s$ is the vector of stator voltage.

According to the equations above, the speed ω can be adjusted by i_{qr}. The control block diagram is shown in Fig. 5.

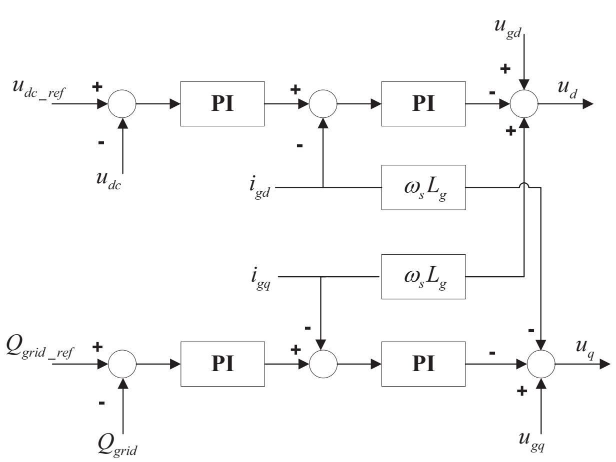

Fig. 2. The model of grid side converter control system.

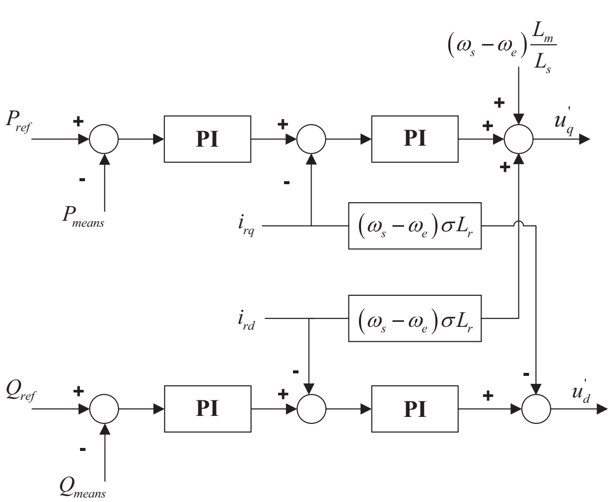

Fig. 3. The model of rotor side converter control system.

3. Dynamic equivalent model of wind farm

In order to simulate the dynamic performance of the wind farm at the point of common coupling (PCC) accurately, it is necessary to maintain the system dynamic output characteristic before and after the equivalence of the wind farm equivalent modeling. At present, the common modeling method for doubly-fed wind farm dynamic equivalence can roughly be divided into two kinds of representations: single-machine representation method and multi-machine representation method. In general, the modeling accuracy and robustness of multi-machine representation is better than single-machine representation.

The following will discuss the two kinds of equivalent modeling methods respectively, and then the calculation method of corresponding equivalent unit parameters is discussed.

3.1. Single-machine representation method

Single-machine representation method refers to the whole wind farm is represented with one wind turbine as the equivalent model. According to the difference of wind speed between all wind turbines, the method can be further classified into "1+1" model (namely one wind turbine with one generator) and "n+1" model (namely n wind turbines with one generator). The classification is given in Fig. 6.

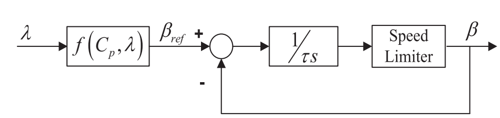

Fig. 4. The model of pitch control system.

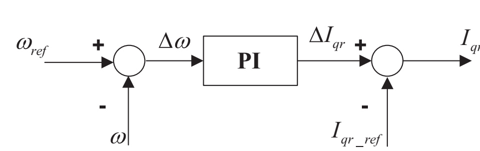

Fig. 5. The model of speed control system.

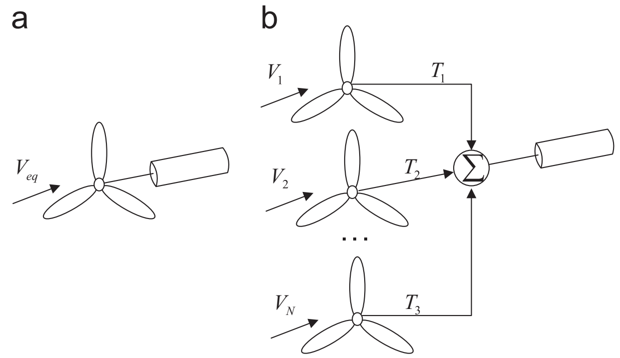

Fig. 6. The classification of single-machine representation method.

3.1.1. "1+1" model

As is shown in Fig. 6(a),"1+1" model takes the equivalent expression of the wind farm as one wind turbine and one generator. In [22], regarding the selection of the input wind speed V_{eq}, a wind farm equivalent model by adopting the average wind speed as the input on the basis of measured operational data in wind turbine is proposed. In [23], the equivalent wind speed with the coefficient of determination method in Statistics is determined, and it is confirmed that the established wind farm equivalent model can be used to calculate the output power of wind farm rapidly under the given wind conditions. In [24], the interference component is considered in wind speed by morphological filter with the same Statistic theory to analysis the measured operational data; It is reported that the input wind speed obtained can reflect the actual wind speed characteristics.

Because of the nonlinear relationship between output power of wind turbines and input wind speed, the above methods commonly result in large deviation. In [25,26], a calculation method for the active power of each wind turbine under the corresponding wind speed on the basis of wind speed–power relationship is proposed, to minimize the equivalent deviation for the wind speed. The wind speed is reversely derived from the output power composition and it is confirmed that the equivalent result of this method is comparatively accurate but has slightly large calculation. Furthermore, the characteristics of the difference for the wind energy utilization coefficient under different wind speed condition is considered in [27], which describes the wind energy utilization coefficient as piecewise function and carrying on the weighting and equivalence for the wind speed. Comparison with the traditional wind speed equivalent method shows the proposed method in [27] not only has little equivalent deviation, but has more simple calculation.

Calculation of parameters for the doubly-fed wind farm equivalent units is usually based on the dynamic model of DFIG and adopted the capacity equal weighted method as in [28]:

$$\begin{cases} S_{eq} = \sum\limits_{i=1}^{m} S_i & P_{eq} = \sum\limits_{i=1}^{m} P_i \\ C_{eq} = \sum\limits_{i=1}^{m} C_i & T_{eq} = \sum\limits_{i=1}^{m} T_i \\ Z_{G\_eq} = \frac{1}{m} Z_G & Z_{T\_eq} = \frac{1}{m} Z_T \end{cases} \tag{15}$$

where m indicates the number of wind turbines, the subscript equtation denotes the parameter after equivalence.

3.1.2. "n+1"model

"$n+1$" model preserves all the wind turbine model and wind speed model but superimposes the mechanical torque of all wind turbines as the input for one equivalent generator, as shown in Fig. 5(b). The computational formula of the equivalent unit parameter is given as follows [28]:

$$\begin{cases} S_{eq} = \sum\limits_{i=1}^{m} S_i & P_{eq} = \sum\limits_{i=1}^{m} P_i \\ T_{M\_eq} = \sum\limits_{i=1}^{m} T_{M\_i} & C_{eq} = \sum\limits_{i=1}^{m} C_i \\ Z_{G\_eq} = \frac{1}{m} Z_G & Z_{T\_eq} = \frac{1}{m} Z_T \end{cases} \tag{16}$$

where T_M denotes the mechanical torque of wind turbine.

Single-machine representation method is suitable for the dynamic equivalent modeling when the wind farm has uniform wind speed distribution or specific conditions. Therefore, when the wind speed between wind turbines has little difference or close operation point, "1+1" model can be employed to build the dynamic equivalent model, but when the wind speed between wind turbines has large difference, "$n+1$"model is considered to obtain better equivalent precision while "1+1" model could result in large deviation as proposed in [29,30]. It should be noted that "$n+1$" model also has the restriction of application in the simulation due to the alteration of the original structure for the wind turbine[31,32].

Besides, the distribution of wind speed in large wind farm is commonly non-uniform by the influence of topography, wake effect and time-lag. Wind turbines are normally working at different operation point. Therefore, the single-machine representation method is difficult to reflect the dynamic characteristics of the whole wind farm comprehensively. Thus, more and more researchers turned their research focus to the multi-machine representation method in recent years.

3.2. Multi-machine representation method

Multi-machine representation method is aimed to build the "$n+n$" model (namely n wind turbine plus n generator) by introducing the idea of coherency-based equivalents [33], which is a common method for dynamic equivalence in the power system, to the dynamic equivalent modeling of the wind farm. The method is based on the principle of unit group that wind turbines have the same or similar operational point to combine the same group of units, and then the target of simplifying the dynamic model of wind farm is achieved. So the determination of unit division method that can reflect the operation characteristic of DFIG is the key point to perform the dynamic equivalent modeling of doubly-fed wind farm with the multi-machine representation method.

Unit division method has intimate relationship with the topography of wind farm and the arrangement of wind turbine. In this paper the wind farm is divided into regular and irregular cases. Their dynamic equivalent methods are summarized in the following section.

3.2.1. Regular wind farm

Regular wind farm is located at the district of oversea or flat terrain. The arrangement of wind turbines in the farm is comparatively regular. Generally, wind turbines are arranged in rows distribution along the main wind direction. From the perspective of Statistics, the same row of those wind turbines has the highly probability to obtain the same input wind speed. The mutual influence between the same row units is also comparatively small, so the wind speed is in good consistency and the farm can be simply classified on the basis of the installation site for the wind turbine.

In [34], an equivalent method with reduced order and variable scale is proposed, which takes each row or each column of wind turbines as one equivalent unit. The application of this method needs to meet two preconditions: (1) the wind farm has the

rectangular arrangement; (2) the wind turbine has the same operation condition. However, the standard rectangular wind farm seldom exists in practical situation, the input wind speed for each row or each column of wind turbines has larger difference. Therefore, the consistency of operational condition for all wind turbines cannot be guaranteed. In view of these situations, another kind of multi-machine representation method is proposed in [35], which has reduced order and variable scale for the exact same unit type. The method is based on the assumption that the input wind speed is almost the same for wind turbines in the same row along the main wind speed direction and the unit is running on the close operational points. So the wind farm can be divided into multiple sections according to the row arrangement and the units in the same section can be combined and equaled further.

The typical wake effect models for the wind farm are Jensen model, Rahman model and Lissaman model [36,37]. The advantage and disadvantage of these wake effect models is studied and compared in [38], the unit division method is given in the paper according to the prevailing wind direction, and the "$n+n$" equivalent model for the wind farm is build in the end to divide the units on the basis of wake effect. The simulation result by comparing with the specific model, "$1+1$" model and "$n+1$" model shows the "$n+n$" model is more consistent with the specific model, the "$n+n$" model is more feasible for the dynamic equivalent modeling of doubly-fed wind farm. In view of wake effect for the flat terrain, the Jensen model to calculate the face velocity of each row along the main wind direction is selected in [39]. The face velocity is then adopted as the input wind speed for each equivalent unit in the equivalent model with advanced reduced order and variable scale. Comparative analysis of numerical example shows the proposed equivalent model can preferably reflect the dynamic operational characteristic for the regular wind farm.

Actually, the unit division method of regular wind farm is based on the wind speed to split the wind turbine group and obtain the multi-machine equivalent model for the wind farm. But wind speed is not the only index in representing the operational status of DFIG. For the complexity of terrain and wind conditions, the arrangement of most wind farms are irregular, therefore, there is a large number of factors to influence the operational point of units for the irregular wind farms. It is likely to appear that the operational point has large difference for the adjacent location but has close characteristic for the far position. So the adoption of the above equivalent modeling method could result in large deviation.

3.2.2. Irregular wind farm

The operational status of DFIG can be reflected with those indexes, including wind speed, rotation rate, active power, reactive power, mechanical torque, stator/rotor current and stator/rotor voltage etc. [40]. The difference of wind speed in different district and the action of DFIG control system in the wind farm is considered in [41], which regards the wind speed and rotation rate as the characteristic variable for dividing the wind turbine, so the proposed method could split the DFIG dynamically in case of failure event according to the dynamic variation of wind speed and rotation rate.

In [42], the following action of DFIG control system subjecting to the case of unit failure is studied, when the operation is at high wind speed, units can adjust the pitch to control the action and limit the output power in the rated range, when the failure occurs, the pitch carries out the corresponding action if the rotation rate exceeds a designated value. Therefore, the pitch control action of DFIG is regarded as the principle of units division. The DFIG is classified into three kinds of cluster in the paper: the pitch is operated in the pre-fault, the pitch is operated in the fault and the pitch is not operated regardless of the fault.

However, the complicate control process and the large number of interference factors in DFIG restrict the judgement and classification with the operation status index and the control action of pitch. More and more literatures are turning to solve the problem by adopting the theory of Support Vector Machine (SVM) and the clustering algorithm.

Support Vector Machine is a machine learning method based on the statistical learning theory. The method has the ability to handle the problem with small sample, nonlinearity and high dimension. It is received widely used in the field of data classification [43]. The basic principle of SVM is to find an optimal hyper-plane that meets the condition of classification. The data that needs to be classified can be then split by the hyper-plane accurately, so the distance of those dates have the maximum interval as shown in Fig. 7. Taken the classification for two types of data as an example, given the training set $\{(x_1, y_1), \ldots, (x_n, y_n)\}, x_i \in R^n, y_i \in \{-1, 1\}$ is the corresponding desired output, n is the total number of specimens, then H is the optimal hyper-plane to guarantee the accurate classification of two types of sample data and make sure the distance between two types of sample points is the maximum [44].

In [42], in order to achieve the purpose of splitting the DFIG dynamically, three feature vectors of wind speed, active power and terminal voltage is extracted, which reflect the control action of the pitch during the fault as the input of SVM categorizer. The simulation result shows the three machine representation method proposed in the reference is more accurate than the single machine representation method, it can reflect the dynamic characteristic of the synchronize point more efficiently during the fault for the doubly-fed wind farm, and the method has certain engineering value in the aspect of analysis and research for grid connected wind farm. In [45], SVM is adopted to classify the wind turbines, but the difference with the above reference is the analysis is based on the measured operational data for the wind farm. Three feature vectors of wind speed, active power and wind turbine status are extracted as the division basis for the wind turbine. Furthermore, wind turbines with the close wind speed variation, close active power variation and same operation style within a certain time interval is classified as a category. The simulation result shows the utilization of SVM categorizer could classify the DFIG into the corresponding cluster by the measured operational data of the above three characteristic variables to meet the demand of the dynamic equivalence for the wind farm.

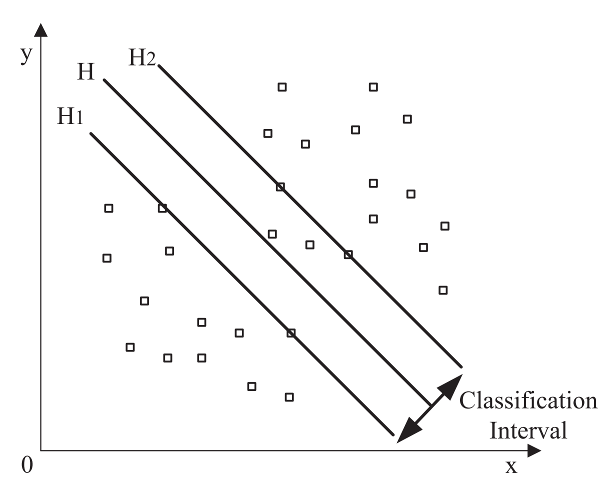

Fig. 7. Optimal hyper-plane (H_1, H_2 are parallel to H and pass through the sample points which are the nearest to H).

In recent years, the utilization of clustering algorithm to classify the DFIG dynamically is also becoming a research focus [46,49,50]. Clustering is a mathematical method to classify the object with certain criterion. The target of this method is to make the similarity of the same object as large as possible and the different object as small as possible [47]. In [48], by analyzing the steady and transient characteristic of DFIG, the voltage equation and flux equation for the doubly-fed generator, 13 status variables is extracted, which can describe the characteristic of operational point as the clustering index of units. K-mean clustering algorithm is used to carry out the clustering analysis for the matrix composed from the 13 index data. In [51], spectral clustering algorithm is adopted to compare the measured operational data of DFIG after classifying the units based on its capacity, then the measured data of wind speed and active power within certain running time is selected as the input of spectral clustering algorithm and the classification result of units for DFIG was finally finished. In [52], spectral clustering algorithm based on the diffusion mapping theory is utilized to find out the unit in a similar dynamical operational characteristic to classify the DFIG dynamically. These literatures all based on the extracted classification index to divide the DFIG and verified the efficiency of the proposed model in different modeling situation by numerical simulations.

In [53], the characteristic root of mechanical transient equation for doubly-fed generator is presented as the classification basis, to classify the wind turbine in the irregular wind farm and make the operational point of units same or similar in the same group. Due to the characteristic root reflects the dynamic characteristic of generator when the voltage has small disturbance, the wind turbine with the similar characteristic value can be classified as a category. In [54], the units of the wind farm is divided according to the response characteristic of speed deviation for the wind turbine in certain special fault, but the proposed method may not be applicable for the classification of wind turbines in other fault. In [55], the initial operational point of each DFIG is determined by flow calculation with the characteristic of speed–power, then based on the wind speed high/low bound that corresponding to the dynamic mutation of transient electric potential to classify the DFIG. In [35], a cluster partition method with the Markov chain basis is proposed, which is combined with the stochastic process theory in the mathematics. The paper excavated the mutual influence interaction between each wind turbine from the statistical point of view. The simulation result shows the proposed method has high accuracy.

In conclusion, the above discussion is aimed at the classification method of units for the irregular wind farm and the numerous factors that affect the characteristic of DFIG at the operational point, it proposed the different division basis for units, and then combined some mathematical statistic method to finish the dynamic clustering of DFIG, the principle of clustering for the accurate classification with the same or similar operational point is satisfied. However, the above literature has different starting point and emphasis point in selecting the classification index, so the selected index cannot reflect the dynamic operational characteristic of DFIG completely. Besides, the common adopted intelligent algorithm has many problems in the application also, such as the SVM needs to determine the categories of units in advance, K-means clustering algorithm easily falls into the local optimal in the case of large data amount, spectral clustering algorithm has complex computation process etc., therefore, the influence on the efficiency of these models should be taken into consideration in the extensive application.

3.2.3. Calculation method for equivalent unit parameter

Multi machine representation method is used to carry out the dynamic equivalent modeling for the DFIG wind farm. After the classification of units, the wind turbines at the same group can be then aggregated with one equivalent unit. From the dynamic model of DFIG it can be seen that the parameter that needs to be equaled includes the capacity, active power, inertial time constant, generator impedance and terminal transformer impedance etc. According to the different focus for the research, the parameter calculation method for the equivalent unit of multi machine representation method can be generally divided into the following three cases:

(1) Capacity equal weighted method [56]
The method is essentially similar to the parameter calculation method of equivalent unit for the single machine representation wind farm. They are all based on the number of units in the same group to calculate the parameter of equivalent wind turbines. The method has the advantage of simple principle and convenient calculation. In [22,31,32,34,37,39], this method is adopted to aggregate the parameter of equivalent unit.
(2) Parameter identification method [57]
The method includes the parameter identification method with the online measurement and the least square. For the nonlinear system such as the wind farm, the former method is complicate to calculate the equivalent parameter, so more researchers focus on the latter one. In [58], the identification method based on the transfer function of DFIG is proposed, and then the least square method is adopted to fit the frequency response of overall transfer function for the units in the same group, finally the paper obtained the equivalent parameter of DFIG. In [59], the output characteristic of wind farm is introduced into the solution process of equivalent parameter, and then proposed to correct the parameter of dynamic equivalent model for the wind farm with the least square method on the basis of information about the current, voltage and power et al. at the connected point.
(3) Objective optimization method
In [60,61], the measured operational data that can reflect the information such as wind speed fluctuation and unit operational status et al. are utilized to build the objective optimization model. Then it adopted the genetic algorithm to calculate the parameter optimization model. The simulation results show the proposed method can calculate the equivalent parameter of equivalent unit precisely, and the obtained dynamic equivalent model can preferably reflect the dynamic characteristic of the wind farm.

4. Conclusion

This paper reviews the research of dynamic equivalent modeling for the wind farm in details. It analyzes the characteristic and application status for the single machine representation method and multi machine representation method. The current research has carried out a lot of works in the field of dynamic equivalent modeling for the doubly-fed wind farm and has made much valuable progress. However, with the increasing of grid connected wind power capacity, in order to meet the demand of the analysis for the dynamic characteristic, the research of dynamic equivalent modeling for the wind farm confronts the following new problem:

1) How to select the classification index for the unit so as to reflect the dynamic operational characteristic of wind turbine generator more comprehensively.
2) How to select the appropriate algorithm of classification for the wind turbine so as to improve the rationality of dynamic classification.
3) How to further simplify the equivalent wind farm of multi machine representation to single machine representation while guarantee the equivalent precision.

In order to solve the continual new problem, it is necessary to research and explore the dynamic equivalent method for the wind farm more deeply. This has great significance to the development of dynamic equivalent modeling technology for the wind farm.

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